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Transformation from homogeneous to nonhomogeneous turbulent flows is developed, based on some properties of the Navier-Stokes equations. This transformation is successfully applied to the turbulent wake, produced by a model-scale frigate. Some new schemes for the large-eddy simulations of turbulent flows are developed, tested by direct numerical simulations and compared with experiments.

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Final Technical Report

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"Structure of turbulence and subgrid-scale modeling"
Program Officer : Dr. Edwin P. Rood
Principal Investigator : Dr. Evgeny Novikov
INLS-UCSD, La Jolla, CA 92093 - 0402

The project has two major goals, driven by the naval engineering (and many others engineering disciplines) :

1) Reduction of the enormous number of degrees of freedom in turbulent flows to a level that is manageable by computer simulations;

2)Transformations from horizontally homogeneous to nonhomogeneous turbulent flows, produced by ships.

The transformations are necessary because the large-eddy simulations (LES) of free-surface turbulent flows with surface piercing bodies are technically difficult.The following form of transformation was developed, as a starting point :

$$v_i = \frac{\partial b_i}{\partial x_k} w_k - b_k \frac{\partial w_i}{\partial x_k} + (c - \frac{\partial b_k}{\partial x_k}) w_i \tag{1}$$

Here velocity w_i , produced by LES, is solenoidal ($\frac{\partial w_k}{\partial x_k} = 0$) and statistically homogeneous in horizontal plane (with a nonlinear free-surface approach or a low Frude-number approximation).Constant c we can put equal to zero for a ship wake, b_i is a deformation of the flow (see below). From (1) it follows that nonhomogeneous velocity fluctuation v_i is solenoidal ($\frac{\partial v_k}{\partial x_k} = 0$). The transformation (1) is suggested by the form of the nonlinear terms in the Navier-Stokes equations, written for vorticity. It can be used also for velocity. The Reynolds stress tensor $< v_i v_k >$ is easy to calculate from (1) with a given realization of w_i and deformation b_i (symbol $<>$ means statistical or volume averaging). For the deformation in a wake the following formula was used, as a first approximation :

$$b_i = T < u_i >, \qquad u_i = < u_i > + v_i \tag{2}$$

Here T is a characteristic time, $< u_i >$ is the mean velocity profile in the wake and u_i is the total velocity field. If we choose T constant,then deformation (2) is

solenoidal and the last term in (1) is zero (with $c = 0$).

These simple formulas in combination with the Smagorinsky LES (SLES) scheme (for horizontally homogeneous turbulence) were compared with measurements of a model-scale frigate wake.The correlation coefficient, calculated in terms of turbulent energy $\frac{1}{2} < v_k v_k >$,is surprisingly high ($\geq$0.80).

In future we plan to test this approach with a more complete data for all components of the Reynolds stress tensor $< v_i v_k >$. The simple transformation (1)-(2) is designed for a distant part of a wake. In order to come closer to a ship, we may need a more general transformation. For example,we can use double transformation : first from horizontally homogeneous turbulence to a distant wake, then from distant wake to a part of the wake, which is closer to a ship.The second deformation $b_i^{(2)}$ should reflect near ship hydrodynamics. We can also combine (1) with a wavelet transformation in order to achieve locality in the spectral content. At the same time,we can use (1)-(2) and their generalizations to calculate Reynolds stresses and, thus, to get closed equations for the mean velocity $< u_i >$.

We made comparison of the SLES scheme with a good experimental data for a high Reynolds number turbulence. SLES reproduces the "-5/3" energy spectrum. However, the third order moment (energy flux), high order moments (intermittency) and probability distribution for the velocity increments, obtained by SLES, deviate significantly from measurements. For future applications, we need a better scheme. We can try some schemes, which we developed in a past (Markov modeling, conditional averaging, incorporation of the intermittency effects in LES, generalization of traditional LES models). But, in order to obtain a reliable scheme systematically, we need a good direct numerical simulations (DNS) data with a substantial inertial range, which means high Reynolds number. To create such DNS data for tree-dimensional (3D) turbulence is very difficult. But we can do it for 2D turbulence [calculations on $(8192)^2$ grid are feasible]. By using local characteristics of 2D turbulence (vorticity gradient) and conditional averaging, we can develope an effective LES scheme, which can be applied to 3D turbulence as well.

In summary, we have two basic issues in the development of this project : 1) LES schemes; 2) transformations from horizontally homogeneous turbulence to nonhomogeneous turbulent flows, produced by ships.

I would like to continue cooperation with experimental laboratory of Mory Gharib at Caltech. In numerical experiments I would like to continue cooperation with Doug Dommermuth at the Science Applications International Corporation.

TECHNOLOGY TRANSFER

Modeling, large-eddy simulation capability and transformation from homogeneous to nonhomogeneous turbulent flows - cooperation with Dr. D. G. Dommermuth and his group at the Science Applications International Corporation.

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